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FFT BASED DIFFERENTIAL PROTECTION FOR POWER TRANSFORMERS

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ABSTRACT

One of the most expensive apparatus in a power system network is the Power Transformer, which needs a continuous monitoring of its health such that the system performs efficiently. Power transformer plays a crucial role in the operation of a power system network and hence its protection adopts the discrimination between internal and external faults. Along with tackling issues related against faults is essential at all times. Of the various methods of protection, available in literature and in practice, the differential protection method is very popular. This method to Current Transformers employed. FFT we have obtained accurate and very useful results.

KEYWORDS: Differential Protection, Power Transformer, FFT, Inrush Current & Internal Fault

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Original Article

INTRODUCTION

Of all the equipment in the power system, transformer protection is in priority as it is in continuous service, apart from it being the most expensive equipment. While the Differential Protection in a transformer, takes care of its internal faults, the proposed scheme is covering the external faults too, providing stability and steady state performance, as seen by the simulation and real time results. The performance of the differential relay would be enhanced, if it were to be provided with the facility to discriminate between the inrush current and a fault current [1].

The various disturbances that may be experienced in different elements of a power system, The electromagnetic-energy storage nature of such elements may produce oscillatory disturbances with The complex characteristics of the elements of the power system produce high frequency transients which can be classified based on duration and magnitudes.[2]–[4]. The proposed technique enables us to overcome the difficulty experienced a differential protection scheme, which cannot discriminate between a fault current and an inrush current, thereby providing the much needed efficient, reliable transformer protection. Current flow through the power system can be of different magnitudes and time characteristics. In order to set up a protective system, the classification of current / voltage / phase etc parameters into healthy and faulty is of great importance. This is even more critical in the protection of transformers, since there are certain conditions which appear faulty but are healthy conditions, such as magnetizing inrush currents.

The principle of operation of any differential protective scheme is that currents in the relay is possible in case of unbalanced input /output relationship. In the event of current flow in the differential relays the circuit breaker is activated by the trip contacts. However under normal conditions, the CT currents are of such a polarity,

that they circulate, rather than flow through the relays.FFT based differential relays have demonstrated accurate, reliable, and fast responses to fault currents without depending on transformer parameters, loading conditions, grounding arrangements.[5]. The proposed technique has achieved the maximum possible detection rate with the minimum number of features used tomonitor the transformer inrush and internal fault currents [8-9].

DIFFERENTIAL PROTECTION OF TRANSFORMERS

The philosophy of differential protection is applied on: power transformers protection, buses protection, large motors and generators protection, and transmission lines protection. The application is based on the Kirchhoff's Current law at the nodes. The principle of differential protection is based on the Comparison between the primary and secondary currents of the power transformer. Current transformers installed in primary and secondary branches of the transformer provide the currents to the relay, which are the operating current (i_D) and the restriction current (i_R). Figure1 illustrates the differential protection scheme for a single phase transformer According to [15], the operation and restriction currents are defined as:

$$i_D = i_1 - i_2 \tag{1}$$

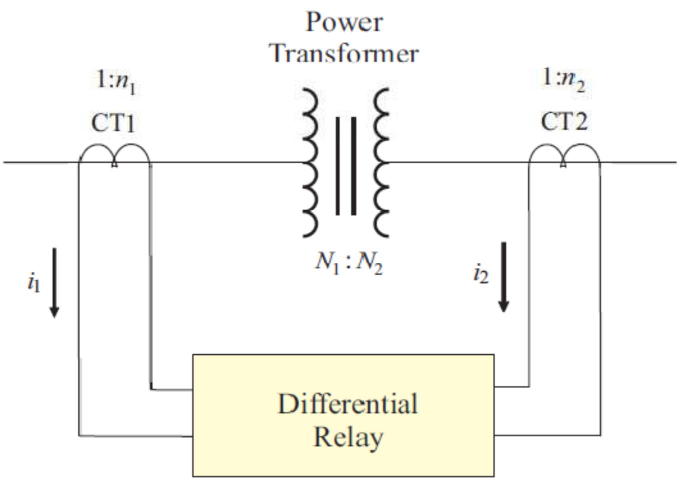

Figure 1: Single Phase Transformer Differential Protection

$$i_R = \frac{i_1 + i_2}{2} \tag{2}$$

On extension of the above to a three phase transformer, under normal operating conditions the CTs transform the primary and secondary currents after considering the transformation ratios, such that i1 and i2 are almost same. For a Y / Δ primary / secondary connected transformer, the CTS are connected Δ / Y of suitable ratio.

The differential protection is based on the comparison between i_D and i_R. Figure 2 depicts an example of a characteristic curve of a differential protection scheme, in which the regions of operation and non-operation are illustrated [15].

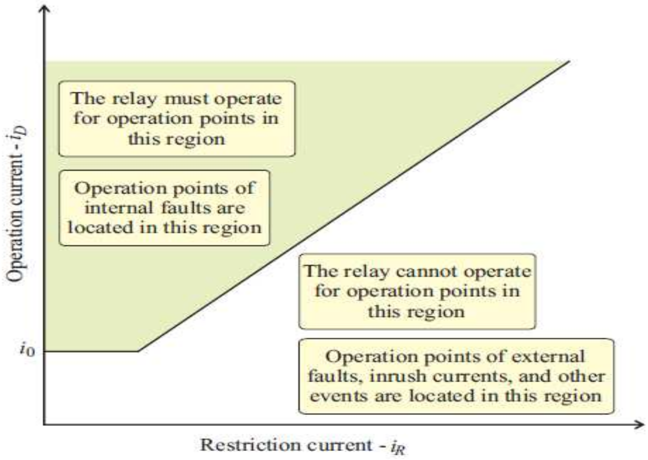

Figure 2 Characteristic Curve of the Percentage Differential Protection

As Figure2 indicates the relay will operate only above the characteristic curve represented by the shaded portion and defined by

$$i_D \succ i_o + ki_R \tag{3}$$

The Current transformers in the market have their own manufacturing standards for the turn's ratio and hence the suitable selection of CTs for transformer protection plays a very crucial role. Since the transformation ratio of transformers is the ratio between the numbers of turns in the primary side to the number of the turns in the secondary side. Therefore, the turn ratio of the primary current transformer is $\frac{1}{N_1}$ and the turn ratio of the secondary side current transformer is $\frac{1}{N_2}$

The secondary current of the CT located in the primary side of the power transformer is [2], [6-7]

$$I_1 = \frac{I_p}{N_1} \tag{4}$$

Where:

I_p : The primary side current of the power transformer,

I_1**:** The secondary side current of CT_1.

N_1**:** The number of turns in the secondary side of CT_1

In the same manner for the CT located at the secondary side of the power transformer, the CT secondary current is:

$$I_2 = \frac{I_S}{N_2} \tag{5}$$

Where:

I_S : Secondary side current of the power transformer

I_2 : Secondary side current of CT_2

N_2 : Number of turns in the secondary side of CT_2

Since the differential current is: $I_d = I_1 - I_2$, then, from equation (4) and equation (5) the

differential current flowing in the relay operating coil current I_d can be calculated as;

$$I_d = \frac{I_p}{N_1} - \frac{I_s}{N_2} \tag{6}$$

If there is no internal fault occurring within the power transformer protected zone, the currents I_1 and I_2 are assumed equal in magnitude and opposite in direction. That means the differential current I_d = 0. The primary and secondary side current ofthe power transformer are related to each other by equation (7)

$$\frac{I_p}{I_s} = \frac{N_s}{N_P} \tag{7}$$

Where:

N_P and N_s : primary and secondary side turns of the power transformer, respectively

$\frac{N_s}{N_P}$: power transformer transformation ratio.

From equation (4) the secondary current with respect to the primary current of the power transformer is [2], [6-7]

$$I_s = \frac{I_p N_p}{N_s} \tag{8}$$

Therefore, by manipulating equations (6) and (8),

$$I_d = \frac{I_p}{N_1} - \frac{I_p X \left(\frac{N_p}{N_s}\right)}{N_2}$$

$$I_d = \frac{I_p}{N_1}\left(1 - \frac{\frac{N_p}{N_s}}{\frac{N_2}{N_1}}\right) \tag{9}$$

$$\lambda = \left(1 - \frac{N_p / N_s}{N_2 / N_1}\right)$$

From equation (6) it is obvious that the term λ must be equal to zero in order to make

$$I_d = 0$$

$$(1 - \frac{N_p / N_s}{N_2 / N_1}) = 0$$

$$\frac{N_2}{N_1} = \frac{N_p}{N_s} \qquad (10)$$

Equation (10) Indicates the Condition for Selection of the CT Turns

Since the transformation ratio of the transformer creates different magnitudes of currents on the primary and secondary sides, for protection, the CTs of the differential scheme are to be properly selected. In case the exact ratio of CTs is unavailable, then interposing CTs may be deployed. However, care is to be taken to consider the additional burden imposed by them. The same argument is applied for three phase (3Φ) transformers, except some extra issues may appear in poly phase transformers. In case of the 3 phase transformers, the star / delta or delta / star connections employed on the primary / secondary sides should be taken care of by connecting a delta / star or star / delta of the Current transformers employed in the protective scheme [20]. As shown in figure 4 the relation between the line-to-line voltage (V_{LL}) to the phase voltage (V_{ph}) can explain the phase shift between

The Δ-Y transformer connection. The following equation gives the relationship between the line-to-line voltage (V_{LL}) to the phase voltage (V_{ph}) [2], [3], [6], [7]

DIFFERENTIAL PROTECTION DIFFICULTIES

The difficulties associated with this protection scheme considering the CTs are a) false tripping b) CT ratio mismatch and

- **Magnetizing Inrush Current**
  - Inrush magnetizing current on charging of the transformer
  - Saturation of CT and their Mismatch
  - Change in transformer ratio because of tap change

Magnetizing Inrush Current

Magnetizing inrush current causes flux levels to shoot up in comparison to normal and hence the currents can be viewed as fault current, by the protective scheme. The magnitude and duration of the magnetizing inrush current is influenced by many factors, some of these factors are [2], [6], [7]

Magnitude and waveform of voltage at the time of CB closing

Magnitude of residual flux in the transformer

Quality and characteristics of Iron Core

Transformer saturation value

Impedance of the circuit

Effect of inrush currents on false tripping.

The inrush current is only on the primary side of the transformer and hence the differential will initiate action of the relay. This is to be recognized by the relay and treated as a healthy condition.

False Trip Due to C.T Characteristics

Due to mismatch of the CTs the differential protection scheme will recognize, a normal healthy condition also as a fault. This too is to be eliminated by using interposing CTs of multi taps[8].

False Trip Due to Tap Changer

On-Load Tap-Changer (OLTC) is installed on the power transformer to control automatically the transformer output voltage. This device is required wherever there are heavy fluctuations in the power system voltage. The ratio of transformation of the CTs can be matched with one position of the On Load Tap Changing Switch. In case the tap changer position is altered then he protective scheme will sense the difference in currents as a fault and initiate action. The other important condition is the saturation of core of the CTs and this too will lead to false operation [9-12].

DIGITAL DIFFERENTIAL PROTECTION

Scores of digital algorithms have been developed and used taking advantage of the computing ability of the computer. The superiority of any algorithm can be best judged by its accuracy and speed. According to IEEE standard the transformer protection should be done with in 100 mSec. In the scenario of many algorithms being available which have 10 times operating speed, this paper describes an algorithm with a speed between 1 and 15 mSec using Fast Fourier Transforms. This algorithm is adapted to increase its speed.

The simulated version of the proposed relay is presented in this paper. The algorithm recognizes the harmonic content in the magnetizing current and the normal current and acts accordingly, initiating the protective action. The amplitude of harmonics decrease progressively and in FFT the signal is decomposed as a set of Sine and Cosine terms given by:

$$f(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} C_K COS(kwt) + S_k \operatorname{Sin}(kwt)$$

Where a 0, Ck, Sk are the dc, Sine and Cosine coefficients. In particular the Ck and Sk are defined as :

$$C_k = \frac{2}{N} \sum_{n=1}^{N-1} X(n) COS(\frac{2kwt}{N})$$

$$S_k = \frac{2}{N} \sum_{n=1}^{N-1} X(n) COS(\frac{2kwt}{N})$$

The harmonic coefficients are given by :

$$F_k = \sqrt{S_k^2 + C_k^2}$$

Where: F_k is the K^{th} harmonic coefficient for k = 1, 2,...,N $x(n)$ and is the signal $f(t)$ in its discrete form. The FFT produces exactly the same results as the DFT; however, the FFT is much faster than DFT, where the speed of calculation is the main factor in this process [13-16].

The flowchart of the algorithm for FFT based relaying is shown in Figure 6 and is explained in steps.

Data Capturing from CTs

For calculation of data, Mod / Id1 – Id2/ = 1, then inrush or internal fault, if Mod / Id1 – Id2/ = 0 then an external fault is detected.

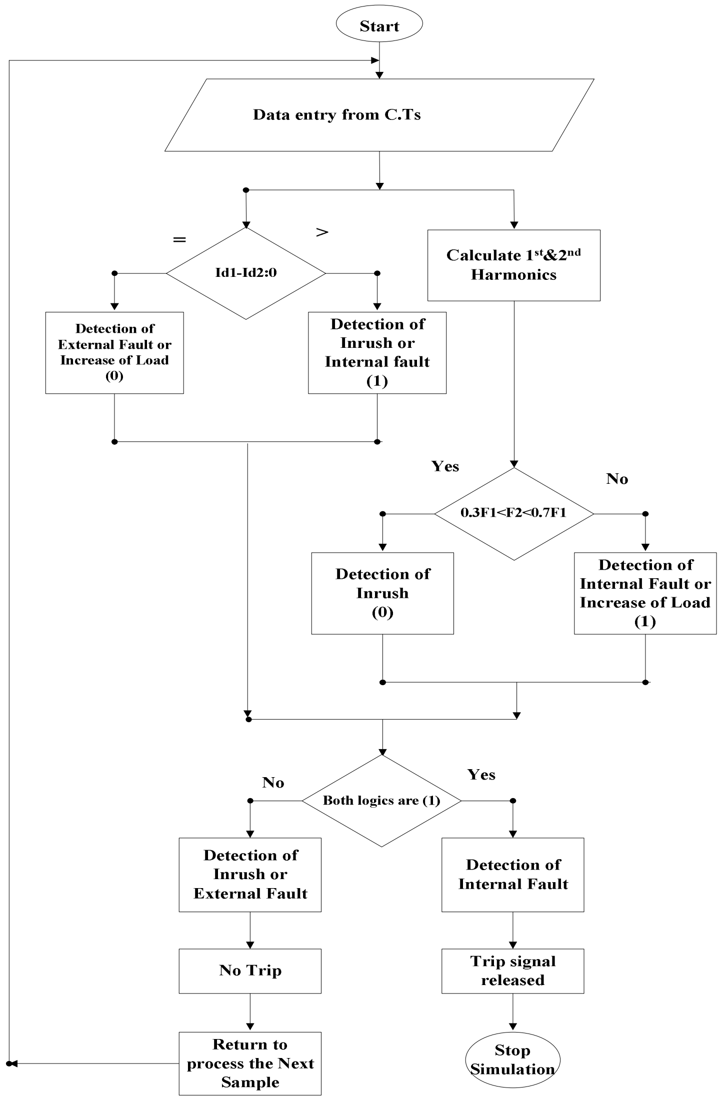

Figure 3: Flowchart for FFT Algorithm

For a value of 0.3 to 0.6 of the fundamental harmonic, which represents the second harmonic, the inrush current is detected and logic goes to 0 otherwise logic takes 1 indicating an external fault

In this step, for both 1 from step 1 and step 2, indicates an internal fault and trip signal is released. Otherwise (0, 1) indicates external fault and (1,0) for magnetizing inrush current and (0,0) the calculation is reset to step 2

Implementation of the FFT for Differential Protection of Power Transformer

The proposed technique is tested on the model of a 3-Φ, 315-MVA, 400/220-kV, 50-Hz core-type Y-Δ power transformer [20]. The 400kVA power transformer is configured as a step-down transformer; its configuration is shown in Figure 1. In this work, the grounding is Implemented using a resistance RG = 0.5Ω and leakage inductance 0.8mH. The ground resistance RG connects the neutral point of the Secondary windings with the ground. The experimental setup used for online tests of both power transformers is shown in Figure7. Two sets of 3 identical CTs, one each on primary and secondary are employed and the methods used to simulate the various faults, was explained earlier.Figure 8 through 12 indicate the designed blocks with their contents.

Coefficient of some are hidden

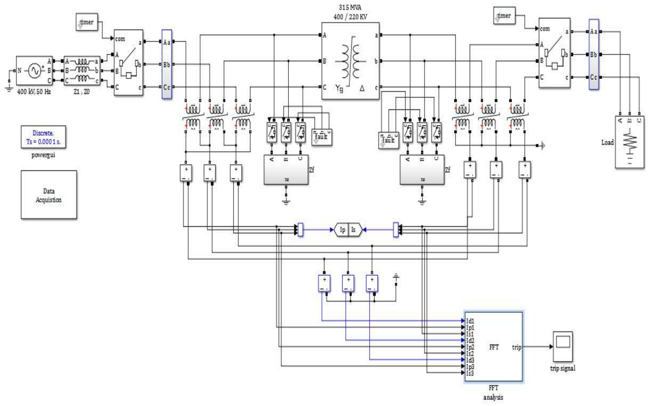

Figure 4: Configuration of Power Transformer

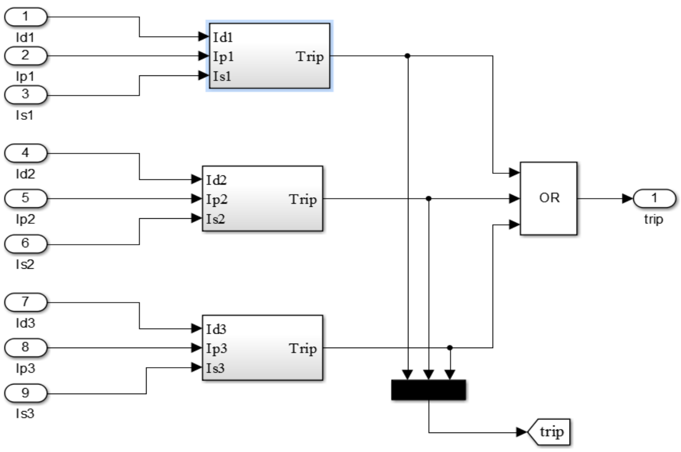

Figure 5: The Differential Relay Block Contents

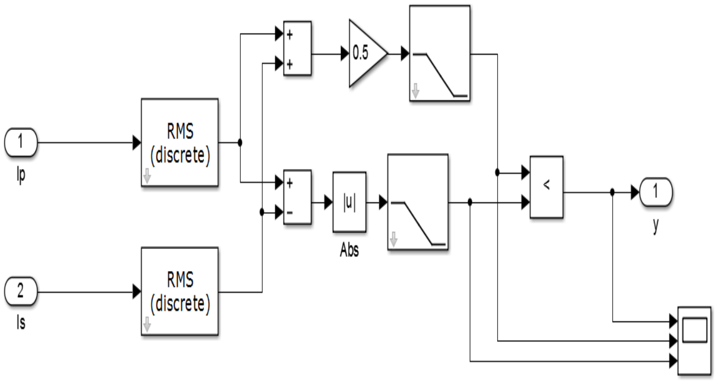

Figure 6: The Amplitude Comparator Block Contents

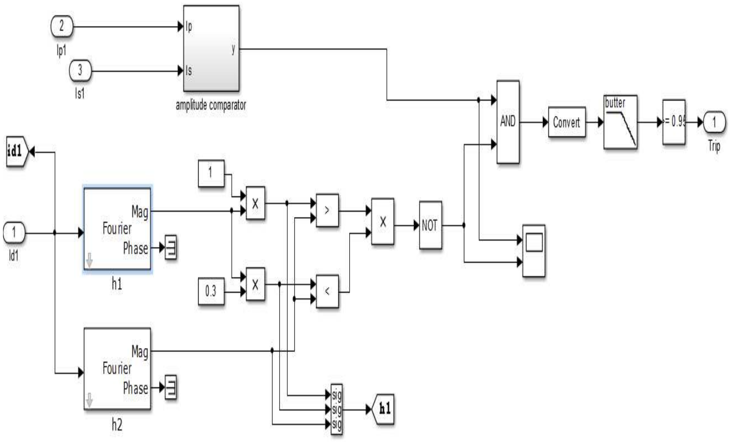

Figure 7: The Harmonic Comparator Block Contents

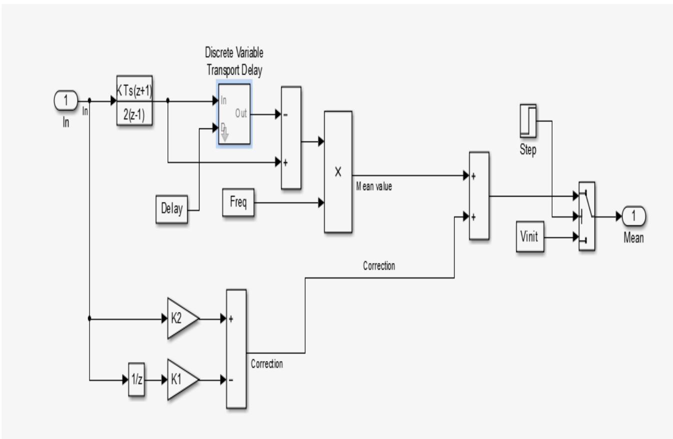

Figure 8: The Ratio Block Contents

SIMULATION RESULTS

The results will be given for different cases:

Case 1: magnetizing inrush current

Case 2: magnetizing inrush with adding load

Case 3: Three phase to ground fault at loaded transformer

Case 4: Phase A to ground external fault at loaded transformer

Other cases of different types of faults and inrush currents such as single line to ground fault, line-to-line fault, line to line to ground fault and three phase fault in both cases loaded and unloaded transformer is illustrated.

Case 1: Magnetizing Inrush Current

In this section of simulation, when the primary side CB1 is closed at 0.25 sec, only the inrush current flows in the primary circuit of the power transformer and no current passes through the power transformer to the secondary side as shown in Figure 9. The harmonic comparator shows in Figure 14 that the value of the 2nd harmonic is higher than 0.3 of the fundamental component.

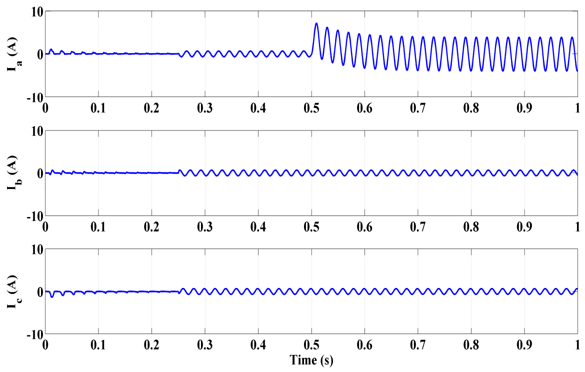

Figure 9: Inrush Currents Waveforms of the Three Phases of the Power Transformer

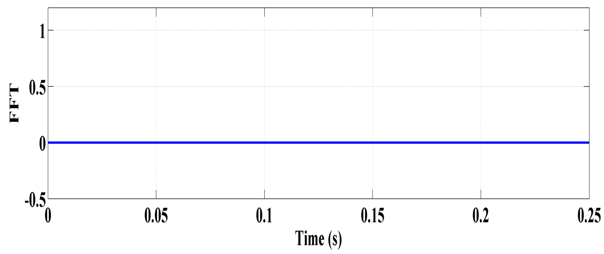

Figure 10: The Responses of the FFT-Based TRIP Signal

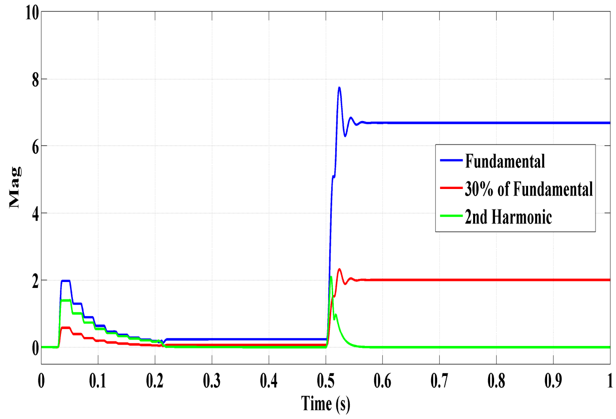

Figure 11: Harmonic Comparator Result: the 2nd Harmonic and the Fundamental Component for the 1stcase

Case 2: Inrush Current on Adding Load

This test is carried out after the energisation of the power transformer by switching ON the CB1 at 0.1sec and CB2 at 0.25 sec from the beginning of the simulation to see the effect of load excursion on the accuracy of the designed approach. Therefore, a 500W resistive load is added to the system at 0.25 sec. Figure 11 indicates the flow of load currents, in the absence of inrush current, the output magnitude being based on CT ratio as designed earlier and depicted in Figure13. Where, before the time 0.25 sec the differential current was equal to the inrush current, but after the swathing ON of the load the differential current went to zero and the primary and secondary currants became equal.

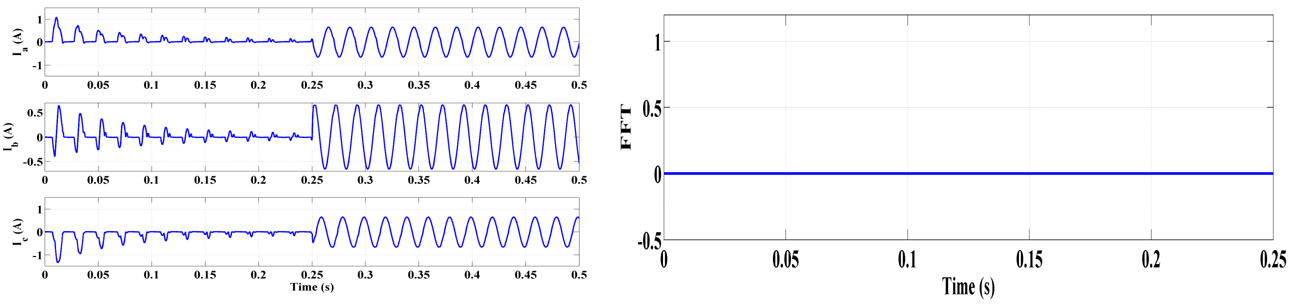

Figure 12: Normal load Current Starts flowing at 0.25 sec

As shown in Figure 12, On switching the CB2, with a lower 2^{nd} harmonic, the logic (1) is released. However the amplitude comparator shows logic (0) which means that for (0, 1) logic no release of trip signal takes place. Figure 13: Shows the Amplitude Comparator Results

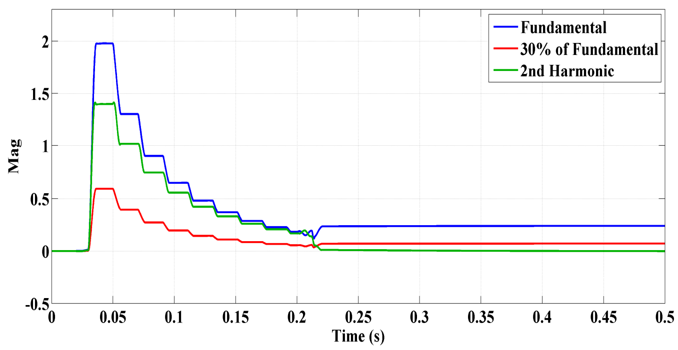

Figure 13: 2nd Harmonic and the Fundamental Component for the 2^{nd}case

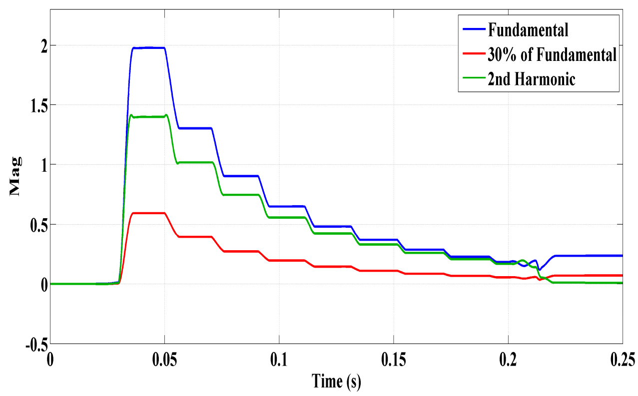

Figure 14: Amplitude Comparator Results for the 2nd Case

Case 3: Three Phase to Ground Fault at Loaded Transformer

The algorithm test the three phase to ground fault security After the switching of CB1 at 0.1sec, an internal fault is created at 2.0 sec at the secondary side of the power transformer by connecting the three phases A, B and C of the secondary side of the power transformer to the ground. In this case, a significant increase of the primary current takes place due to the fault occurrence inside the protected zone at 2.0 sec as shown in Figure 14.Harmonic and amplitude comparators give the result as an internal fault as a result the transformer is isolated from the grid. Also it is obvious from Figure 15 that the relay has released a trip signal after 2.09 sec after the occurrence of the fault, which can be considered as a very good speed to isolate the transformer.

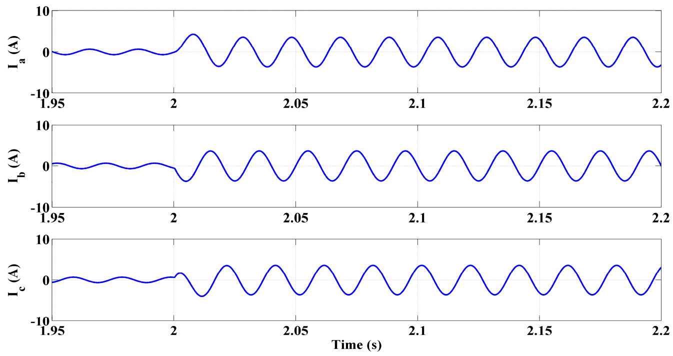

Figure15: Increase of Phase A, B & C Currents Due to the Occurrence of the fault at 2.0 sec for Loaded Transformer

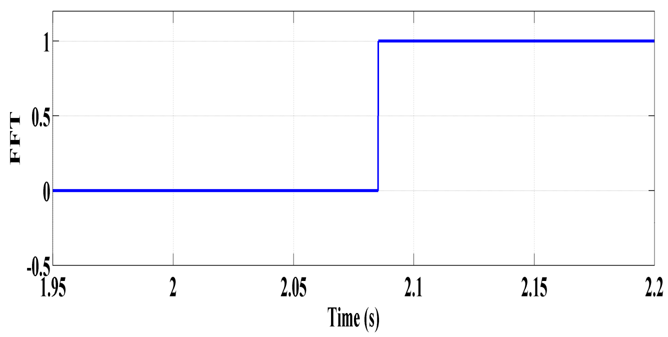

Figure16: C Zoomed

Case 4: Loaded Transformer with phase A to Ground External Fault

Similar to case 2, where in the faults outside the protected zone, is reflected in both sides of the transformer showing an increase of currents this is treated as an increase in load current by the relay and hence no trip signal is released. as in Figure 23 trip signal, trip time is around 2.09 sec

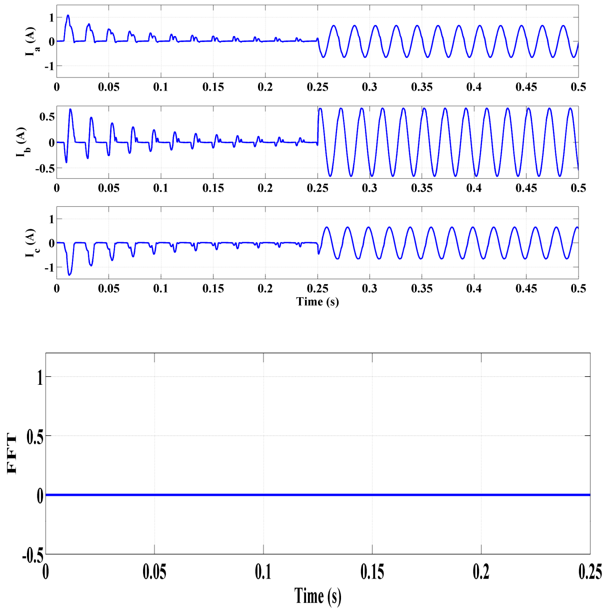

Figure 17: Increase of Phase a Current Due to the Occurrence of the Fault at 0.25 sec for Loaded Transformer

CONCLUSIONS

In this paper, the implementation and simulation of a small power system with a differential protection for the power transformer. The implementation is shown in step by step. This simulation is tested for various cases and for all cases it gave satisfactory Results. All the tests gave satisfactory results.

The different and unpredictable characteristics of magnetizing inrush currents did not appreciably affect the ability of the FFT based differential protective relay to diagnose them as non fault currents. The proposed technique includes a new approach for Discrimination between magnetizing inrush and internal faults. The results show that the proposed algorithm was also quick and accurate.

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